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Environmental Cracking of Corrosion Resistant Alloys in the Chemical Process Industry - A Review

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ENVIRONMENTAL CRACKING OF CORROSION RESISTANT ALLOYS IN THE CHEMICAL PROCESS INDUSTRY – A REVIEW

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ABSTRACT

A large variety of corrosion resistant alloys are used regularly in the chemical process industry (CPI). The most common family of alloys include the iron (Fe)-based stainless steels, nickel (Ni) alloys and titanium (Ti) alloys. There also other corrosion resistant alloys but their family of alloys is not as large as for the three groups mentioned above. All ranges of corrosive environments can be found in the CPI, from caustic solutions to hot acidic environments, from highly reducing to highly oxidizing. Stainless steels are ubiquitous since numerous types of stainless steels exist, each type tailored for specific applications. In general, stainless steels suffer stress corrosion cracking (SCC) in hot chloride environments while high Ni alloys are practically immune to this type of attack. High nickel alloys are also resistant to caustic cracking. Ti alloys find application in highly oxidizing solutions. Solutions containing fluoride ions, especially acid, seem to be aggressive to almost all corrosion resistant alloys.

Keywords: Environmentally Assisted Cracking, Stainless Steels, Nickel Alloys, Titanium, Chloride, Hydrochloric, Caustic

INTRODUCTION

The chemical process industry (CPI) provides the basic ingredients of many other industries, technologies and products. For example, the CPI manufactures the hydrofluoric acid that the semiconductor manufacturer uses for the etching of the wafers. The CPI includes the traditional organic and inorganic chemical industries, the petroleum industry and the petrochemical industry (manufacturing of plastics and synthetic fibers). In general, since in the CPI raw materials need to be converted to simpler or purer materials, highly aggressive conditions exist in this industry both in term of high temperatures and extreme pH values. These conditions are necessary to transform the raw materials into desirable

products. One of the most common failures associated with equipment used in the CPI is environmentally assisted cracking (EAC).

EAC is a general term that includes events such as stress corrosion cracking (SCC), hydrogen embrittlement (HE), hydrogen assisted cracking (HAC), sulfide stress cracking (SSC), liquid metal embrittlement (LME), corrosion fatigue (CF), etc. EAC refers to a phenomenon by which cracks may propagate in a brittle manner in an otherwise ductile alloy when it is subjected to mechanical tensile stresses in presence of a specific corroding environment. For EAC to occur, three affecting factors must prevail simultaneously. These are: (1) Mechanical tensile stresses, (2) A susceptible metal microstructure and (3) A specific aggressive environment. If any of these three factors is removed, EAC will not occur. This is the method that many design engineers use to mitigate the occurrence of EAC, for example, by eliminating residual stresses in a component or, by limiting the application of the component to certain non-aggressive chemicals (environment). The term environment not only includes the chemical composition of the solution in contact with the component but also other variables such as temperature and the redox potential in the system.

In general, to combat or minimize EAC, engineers in the CPI have to rely on mutual support to understand the chemicals-materials interaction. There are organizations, such as the Materials Technology Institute (MTI) of the CPI, that were created to assist plant engineers dealing with the everyday corrosion issues. However, engineers are faced generally with a limited budged for in-house research regarding materials-environment interaction and many times do not have the financial support from management in order to recommend newer more corrosion-resistant (and more expensive) materials.

Even though a large variety of materials are used in the CPI, such as glass, plastics, composites, metallic alloys and others, this paper only focuses on the behavior of the family of corrosion resistant alloys of stainless steels, nickel alloys and titanium (Table 1).

MATERIALS CHALLENGES IN THE CPI

The selection of materials for a component to be used in the CPI can be at times a difficult task. In many cases the material needed to withstand a board-designed process does not actually exist. So engineers have to do the best they can with what they have. It is important to know as much as possible about the operating conditions of the component, what are the most aggressive species in the stream, what is the concentration and what is the temperature. Are any spikes in temperature or pressure expected during the normal operating conditions? It is also important to know if the process is going to go through frequent shut-down and start-up procedures and what is the total expected lifetime for the component.

In most of the wet applications (e.g temperatures below 538°C or 1000°F), requirements of mechanical strength are generally secondary to the chemical compatibility of the material with the environment. That is, it is more important the value of the corrosion rate of the alloy in question under normal operating conditions than the mechanical strength of the selected material. However, if the component is under stress in the corrosive milieu, the possibility of applied stress and EAC also needs to be considered.

In most of the simple environments (such as non-contaminated acids) corrosion rate data exists for most commercial alloys. Therefore, the selection of materials for general corrosion resistance is not an insurmountable challenge. However, the selection of materials to resist EAC is more problematic since testing for EAC is more complex and therefore fewer reliable data exist. Moreover, most of the data available is from laboratory testing. It is almost impossible to reproduce in the laboratory the service conditions both in terms of environment (mixture of species, fluctuation in temperature, etc.) and

operating conditions (for example sudden changes in pressure that may manifest as a intricate state of stresses on the component).

CORROSION PROPERTIES OF THE CORROSION RESISTANT ALLOYS

Stainless steels, Ni and Ti alloys, the same as other alloys, may suffer two main types of corrosion, uniform corrosion and localized corrosion. Uniform corrosion may happen under reducing conditions in the active region of potentials and also under oxidizing conditions in the form of a slow passive dissolution. Localized corrosion such as pitting and crevice corrosion generally occurs under oxidizing conditions. EAC or stress corrosion cracking (SCC) could occur at any electrochemical potential range. In many alloy systems, SCC is also associated to specific potential windows, for example, in the anodic region in a certain range of potentials or in the cathodic region, below a threshold potential.

Stainless steels and nickel (Ni) alloys are extensively used in chemical process and other industries where aggressive environments could be found. These alloys resist aggressive solutions mainly by the formation of passive films, which slow down the rate of corrosion. For example, in nitric acid (HNO_3), alloys with a high content of chromium (Cr) (e.g. N06030) are the recommended alloys since chromium oxide (Cr_2O_3) is stable in oxidizing acidic conditions. In reducing conditions, such as hot hydrochloric acid (HCl) solutions, a recommended alloy should contain an important proportion of molybdenum (Mo). In hot HCl solution, Cr_2O_3 is not stable. [1]

In general, individual nickel alloys can be more resistant to general and localized corrosion than stainless steels, basically because nickel can dissolve a larger amount of beneficial alloying elements than iron and therefore nickel alloys can be tailored to more specific applications. This is particularly true in the case of hot HCl in which a large amount of Mo is needed. Nickel alloys of the B family, which contain up to 28% Mo are the recommended alloys for HCl service. Stainless steels can contain only a maximum of 6-7% Mo. The same can be said regarding the resistance to localized corrosion such as pitting corrosion and crevice corrosion in chloride (Cl^-) containing environments. The beneficial elements protecting against localized corrosion induced by chloride ions are Cr and Mo. The factor of protection is called the pitting resistance equivalent (PRE) and is generally defined for stainless steels as PRE = Cr + 3.3 Mo where the element symbol represents the weight percent of the element in the alloy. Nitrogen (N) and tungsten (W) are also a beneficial elements against localized corrosion and a modified factor can be defined as PREN = Cr + 3.3 (Mo + 0.5 W) + 16 N. The higher the PRE the more resistant the alloy to chloride promoted localized corrosion. The maximum PRE that can be reached with austenitic wrought stainless steels is approximately 45 (e.g. in N08367) but with wrought nickel alloys, the high PRE factors can be in the order of 76 (e.g. N06059) (Table 1).

In general nickel alloys are more resistant than stainless steels to EAC. Austenitic stainless steels (such as S30400) suffer SCC in presence of hot aqueous solutions containing chloride ions. Since chloride ions are ubiquitous in most industrial applications, the use of stainless steels components containing sometimes only minimal residual stresses is seriously limited because of the chloride cracking. On the other hand, nickel alloys (such as C-276 or N10276) are to all intents and purposes immune to SCC in presence of hot chloride solutions and therefore an excellent alternative to replace the troubled austenitic stainless steels. Nickel alloys may be prone to EAC in other environments such as hot caustic and hot wet hydrofluoric acid. [2-5] In some environments such as hot caustic solutions, both stainless steels and nickel alloys are prone to EAC (Table 1).

The main application of Ti alloys is under oxidizing conditions where the alloys develop a strongly adherent and inert passive film. Titanium is also used in seawater because to its resistance to chloride-induced localized corrosion such as pitting corrosion and crevice corrosion. Titanium cannot tolerate fluoride ions, which readily attack its passive film and therefore causes higher than acceptable corrosion rates. Ti cannot be used either in dry chlorine conditions. A few ppm of water in presence of chlorine makes Ti resistant to corrosion.

THE FAMILIES OF STAINLESS STEELS, NICKEL AND TITANIUM ALLOYS

Stainless Steels (SS) are solid solutions of iron (Fe). The alloying with Cr makes them stainless, by the development of a Cr_2O_3 film on the surface. Commercial stainless steels can generally be divided in four large groups: (1) Martensitic and Ferritic, (2) Austenitic, (3) Superaustenitic and (4) Duplex (Table 1). [6-9] The content of Cr in the stainless steels varies from approximately 12% in the martensitic to approximately 30% in some ferritic. Some austenitic steels contain Mo, Copper (Cu), N and other elements for enhanced corrosion performance (Table 1). Mo and N are added for resistance to localized corrosion such as pitting and crevice corrosion. Cu is generally added to offer protection in sulfuric acid (H_2SO_4) and hydrofluoric acid (HF). The microstructure of ferritic steels is body centered cubic (bcc) and of the austenitic is face centered cubic (fcc). The duplex stainless have both microstructures, approximately 50% of each one. Age hardenable steels have second phases for extra strength. The ductility of the stainless steels can vary from less than 5% for the martensitic to approximately 40% for the austenitic. The ultimate tensile stress (UTS) can vary from less than 500 MPa for some ferritic and austenitic to more than 1000 MPa for the martensitic and age hardenable steels.

Nickel alloys are solid solutions based on nickel (Ni). There are two large groups of the commercial Ni alloys. One group was designed to withstand high temperature and dry or gaseous corrosion while the other is mainly dedicated to low temperature (aqueous) applications. Nickel alloys used for low temperature aqueous or condensed systems are generally known as corrosion resistant alloys (CRA) and nickel alloys used for high temperature applications are known as heat resistant alloys (HRA) or high temperature alloys (HTA). The practical industrial boundary between high and low temperature nickel alloys is in the order of 500°C (or approximately 1000°F). There are five basic families of corrosion resistant Ni alloys (Table 1): (1) commercially pure Ni, (2) Ni-Copper (Cu) alloys, (3) Ni-Mo Alloys, (4) Ni-Cr-Mo Alloys and (5) Ni-Cr-Fe Alloys. Even though Ni alloys in general contain a large proportion (sometimes up to 50%) of other alloying elements, nickel alloys still maintain the face centered cubic lattice (fcc) or austenitic microstructure from the Ni base element. As a consequence of the austenitic structure, nickel alloys have excellent ductility, malleability and formability. Nickel alloys are also readily weldable.

Contrary to stainless steels and nickel alloys that can have up to 30-50% or their weight in alloying elements, Ti alloys rarely contain more than 10% of alloying elements. One of the most alloyed Ti alloy is Grade 5, which contains 6% aluminum (Al) and 4% vanadium (V). Ti alloys are known by grades. There are actually around 30 different grades. The chemical compositions are given in ASTM B 265. [10] The most popular Ti alloy is Grade 2 (R50400), which is the commercially unalloyed Ti (Table 1). The most corrosion resistant Ti alloy is Grade 7, which contains a small amount of palladium (~ 0.15% Pd), to make it more resistant under reducing acidic conditions.

COMMON ENVIRONMENTS CAUSING ENVIRONMENTAL CRACKING IN CORROSION RESISTANT ALLOYS

Table 2 shows the most common environments that cause cracking in stainless steels, Ni and Ti alloys. Basically the most common environments that cause EAC of nickel alloys also cause cracking of stainless steels. [11] However, some stainless steels may suffer EAC in conditions where nickel alloys are not susceptible. The later include hot chloride solutions. Some austenitic stainless steels (e.g. Type 304 with 8% Ni) are exceedingly susceptible to chloride cracking. One of the common problems is the chloride cracking under insulation, when the chloride causing the damage is not related to the industrial process under consideration. [12] Other austenitic stainless steels with higher Ni content are practically immune to chloride cracking. [13] High strength martensitic stainless steels are also more susceptible to hydrogen cracking than nickel alloys.

Ti alloys in general suffers EAC in different environments than those of stainless steels and nickel alloys. [14] Some of these include nitric acid and methanol. [11] Most of the failures in Ti alloys are associated to the ingress of hydrogen into the matrix causing hydrogen embrittlement (HE).

STRESS CRACKING IN CAUSTIC ENVIRONMENTS

Caustic or strongly alkaline environments are rather common in the CPI. They refer usually to highly concentrated solutions of sodium hydroxide (NaOH) or caustic soda, potassium hydroxide (KOH) or caustic potash and calcium hydroxide ($Ca(OH)_2$) or caustic lime. [11] High temperature caustic environments containing sometimes over 50% of alkalis are found in many industries including the CPI.

The most common material to handle caustic environments is carbon steel if the contamination by iron can be tolerated. Carbon steels suffer high corrosion rates at temperatures above 80°C and caustic cracking maybe expected. [11] Ni containing carbon steels may be used for a wider and more aggressive ranges of caustic applications. Stainless steels such as austenitic Types 304 (S30400) and 316 (S31600) seem even less reliable than carbon steel for caustic service. The application limits for the austenitic SS are 50% caustic and 70°C to 90°C. [11,15] The 300 series of SS also suffer caustic cracking at temperatures above 100°C. [8,15] The cracking susceptibility of either 304 or 316 SS is the same and sensitization does not seem to play a role. [15] Likely, applications of stainless steels for caustic service include piping, valves, pumps and equipment. Problems rarely occur when the NaOH concentration is limited to 10-20%. [15]

NACE International prepared the Standard Recommended Practice RP0403-2003 for avoiding caustic stress corrosion cracking of carbon steel refinery steel and piping. [16] This recommendation includes the Caustic Soda Service Chart. This chart allows non-stress relieved carbon steel to be used for caustic service up to 140°F (60°C) for NaOH concentrations up to 30% (Area A in the Chart) (Figure 1). Stress-relieved carbon steel is recommended to be used in conditions delineated by Area B. The maximum temperature for Area B is approximately 230°F (110°C) at 20% NaOH and decreases to approximately 170°F (~80°C) at 50% NaOH. In the Area C, for temperatures higher than 110°C, only nickel alloys are recommended for all concentration of caustic soda. [16]

The best metallic material overall to handle caustic solutions at all concentration and temperatures is Ni-200 (N02200). Ni-200 can be used even in molten anhydrous NaOH at temperatures as high as 538°C (1000°F). Figure 2 shows the general corrosion rate by weight loss of several alloys of interest. [1,17] The higher the Ni content the lower the corrosion rate. Ni-200 may be still slightly susceptible to caustic cracking but mainly at temperatures higher than 300°C. [11] Others consider Ni-200 practically immune to caustic cracking. [15] Other high nickel alloys such as Alloy 600 (N06600) can also be used to handle hot caustic environments but after prolonged service it will also develop cracks. [11] Ni alloys such

as C-276 or B-2 may not be recommended since they suffer dealloying by the preferential dissolution of Mo from the alloy. The most likely mechanism by which stainless steels and nickel alloys suffer caustic cracking is via an anodic dissolution process. [4]

Titanium is usually not recommended for caustic service, especially at high hydroxide concentration and at high temperature due to higher than acceptable general corrosion rates. Ti alloys may be prone to cracking in caustic media. The most likely manner by which Ti can suffer EAC in caustic conditions is via a HE mechanism. [18]

CRACKING IN HOT CHLORIDE SOLUTIONS

Austenitic stainless steels, especially in the 300 series, are notorious for suffering cracking in presence of hot chloride-containing solutions. It is apparent that the simultaneous presence of chloride and heat transfer through the stressed component is especially detrimental. [11] If evaporation does not occur on the stressed surface the effect of chloride is less important. The increased presence of nickel as an alloying element in the stainless steels reduces even further the detrimental effect of chloride. Alloys such as 20 or 28 containing 32-35% Ni (Table 1) are less susceptible to chloride cracking than the 300 series of austenitic stainless steels. [11,19-20] The initial study on the effect of Ni on the EAC susceptibility of stainless steels is generally known as the Copson curve, [19-20] Duplex stainless steels also offer great resistance to chloride cracking since the ferritic phase is not susceptible to cracking. The susceptibility of the different stainless steels to chloride cracking is discussed in detail by Sedriks. [19-20]

Nickel alloys are resistant to chloride cracking, basically because they generally contain more than 50% of Ni. However at higher temperatures (higher than ~200°C), Ni based alloys may suffer cracking in acidic chloride solutions, especially when in the cold worked and in the high temperature thermally aged conditions.

Ti and Ti alloys are not susceptible to chloride cracking in the same sense as stainless steels do. High strength Ti alloys may suffer environmental cracking but at higher temperatures than the stainless steels (>250°C) and generally only in laboratory testing. Cracking caused by chloride is seldom observed in service. [21] The cracking mechanism of Ti maybe more related to HE than to the typical chloride cracking.

HYDROGEN EMBRITTLEMENT

Austenitic stainless steels are not highly susceptible to hydrogen assisted cracking (HAC) or hydrogen embrittlement (HE), basically because of their low strength (Table 1). [20] Higher strength stainless alloys such as the martensitic are prone to HAC. NACE Standard MR0175 gives guidelines for materials selection to be used where HE may be expected based on strength of the alloy. The mechanism of cracking by hydrogen of stainless alloys maybe different than for titanium alloys. The occurrence of both HAC and HE is not generally associated with the presence of chlorides in the electrolyte. The common denominator for hydrogen cracking to occur is that the potential of the part in service is at a potential that is below the hydrogen evolution reaction potential described by the Nernst equation. This allows to nascent hydrogen to evolve on the surface of the stressed material and some of this hydrogen gets absorbed and dissolved in the matrix. High strength stainless steels generally dissolve hydrogen in atomic form in the lattice while titanium reacts with the nascent hydrogen to form brittle hydrides.

Hydrogen embrittlement of stainless steels can be minimized by controlling the amount of residual hydrogen in the steel. Even if hydrogen ingresses into the steel component, cracking many times

does not occur. Also, if the environmental conditions change and further hydrogen is not pumped into the steel, the steel can regain ductility because the pre-existing hydrogen eventually diffuses away.

Nickel alloys may also be prone to HE, especially for alloys which do not have a high elongation to failure. High temperature (~700°C) heat treatment of Ni alloys may make them susceptible to cracking in acidic solutions. The thermally aged Ni-Mo alloy (N10665) suffered cracking at cathodic potentials when exposed to hot acidic solutions. [22]

The case of HE of Ti alloys may be different from stainless steels since Ti reacts with the incoming atomic hydrogen to form brittle hydrides. However, laboratory experiments have shown that three conditions usually exist simultaneously for hydriding to occur in titanium alloys: [23] (1) The pH of the solution is less than 3 or greater than 12; the metal surface must be damaged by abrasion; or impressed potentials are more negative than -0.70V, (2) The temperature is above 170°F (77°C) or only surface hydride films will form which, experience indicates, do not seriously affect the properties of the metal. Failures due to hydriding are rarely encountered below this temperature. (There is some evidence that severe tensile stresses may promote hydriding at low temperatures.), (3) There must be some mechanism for generating hydrogen. This may be a galvanic couple, cathodic protection by impressed current, corrosion of titanium, or dynamic abrasion of the surface with sufficient intensity to depress the metal potential below that required for spontaneous evolution of hydrogen. [23]

CRACKING IN WET HYDROFLUORIC ACID

The cracking of stainless steels and nickel alloys in wet hydrofluoric acids is discussed separately. [5] Titanium alloys suffer high general corrosion rates in HF and it is never recommended for this type of application.

SUMMARY

1. The CPI employs a wide range of corrosion resistant alloys. The most common alloys are stainless steels, nickel alloys and titanium

2. All environments that cause cracking of nickel alloys also cause cracking of stainless steels

3. Nickel alloys are practically immune to cracking in chloride containing solutions

4. Chloride cracking can be combated by using high nickel stainless steels or nickel based alloys

5. High Ni alloys offer resistance to cracking in caustic solutions

6. Only the stainless steels with high strength may be prone to hydrogen embrittlement

7. Ti alloys, and mostly high strength Ti, may suffer hydrogen embrittlement

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DISCLAIMER

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TABLE 1
APPROXIMATE CHEMICAL COMPOSITION AND TYPICAL MECHANICAL PROPERTIES OF CORROSION RESISTANT ALLOYS

Alloy	**UNS**	**Approximate Composition**	**YS 0.2% (MPa)**	**UTS (MPa)**	**ETF (%)**
		Stainless Steels			
410[A]	S41000	86Fe-12Cr-1Mn-1Si-0.10C	965	1241	15
440C[A]	S44004	80Fe-17Cr-1Mn-1Si-1C	1896	1965	2
17-4 PH [B]	S17400	74Fe-16Cr-4Ni-4Cu-1Mn-1Si-0.3Nb	1275	1378	14
430	S43000	83Fe-17Cr-0.12C	205	450	22
Sea-Cure	S44660	67Fe-27.5Cr-3.4Mo-1.7Ni-0.4Ti-0.02C	450	585	18
AL 29-4C	S44735	66Fe-29Cr-4Mo-1Ni-0.03C	415	550	18
304	S30400	72Fe-19Cr-9Ni-0.08C	205	515	40
316	S31600	71Fe-17Cr-12Ni-2.5Mo-0.03C	205	515	40
AL-6XN	N08367	46Fe-21Cr-24Ni-6.5Mo-2Mn-0.22N-0.03C	310	655	30
254 SMO	S31254	55Fe-20Cr-18Ni-6.3Mo-1Mn-0.2N-0.02C	310	655	35
20Cb-3	N08020	37Fe-20Cr-35Ni-2.5Mo-2Mn-3.5Cu-0.07C	241	551	30
28	N08028	34Fe-27Cr-32Ni-3.5Mo-2.5Mn-1Cu-0.03C	215	500	40
904L	N08904	46Fe-21Cr-25Ni-4.5Mo-2Mn-1.5Cu-0.1N-0.02C	215	490	35
2205	S31803	69Fe-22Cr-5.5Ni-3Mo-0.14N-0.03C	450	620	25
255	S32550	64Fe-25Cr-6Ni-3.3Mo-2Cu-0.2N-0.04C	550	760	15
2507	S32750	69Fe-25Cr-7Ni-4Mo-0.28N-0.03C	550	795	15

TABLE 1 - CONTINUED

Nickel Alloys

200	N02200	99Ni-0.2Mn-0.2Fe	190	450	50
400	N04400	67Ni-31.5 Cu-1.2Fe	270	540	43
B-2	N10665	72Ni-28Mo	407	902	61
B-3	N10675	68.5Ni-28.5Mo-1.5Cr-1.5Fe-	400	885	58
B-4	N10629	65Ni-28Mo-4Fe-1Cr-0.3Al	340	755	40
600	N06600	76Ni-15.5Cr-8Fe	275	640	45
690	N06690	62Ni-29Cr-9Fe	334	690	50
800	N08800	45Fe-33Ni-21Cr-0.4Ti			
825	N08825	43Ni-21Cr-30Fe-3Mo-2.2Cu-1Ti	338	662	45
G-30	N06030	44Ni-30Cr-15Fe-5Mo-2Cu-2.5W-4Co	317	689	64
33	R20033	31Ni-33Cr-32Fe-1.6Mo-0.6Cu-0.4N	380	720	40
C-276	N10276	59Ni-16Cr-16Mo-4W-5Fe	347	741	67
C-4	N06455	65Ni-16Cr-16Mo	335	805	63
625	N06625	62Ni-21Cr-9Mo-3.7Nb	535	930	45
C-22	N06022	59Ni-22Cr-13Mo-3W-3Fe	365	772	62
C-2000	N06200	59Ni-23Cr-16Mo-1.6Cu	345	758	68
59	N06059	59Ni-23Cr-16Mo-1Fe	340	690	40
686	N06686	46Ni-21Cr-16Mo-4W-5Fe	364	722	71
21	N06210	60Ni-19Cr-19Mo-1.8Ta	370	775	64
C-22HS *	NA	61Ni-21Cr-17Mo	742	1232	50
725HS *	N07725	57Ni-21Cr-8Mo-9Fe- 3.4Nb-1.4Ti	1043	1375	25

Titanium Alloys

Ti Gr 2	R50400	~99Ti	275	345	20
Ti G 5	R56400	Ti-6Al-4V	828	895	10
Ti Gr 7	R52400	Ti-0.15Pd	275	345	20
Ti Gr 12	R53400	Ti-0.3Mo-0.8Ni	345	483	18

Mechanical Properties at ambient temperature YS = Yield Strength, UTS = Ultimate Tensile Strength, ETF = Elongation to Failure, A = Quenched and Tempered, B = Precipitation Hardenable, NA = Not Available, * Age Hardened

TABLE 2
ENVIRONMENTS THAT MAY CAUSE ENVIRONMENTALLY ASSISTED CRACKING OF STAINLESS STEELS AND NICKEL ALLOYS

Alloys	Common Environments that May Cause Cracking
Stainless Steels	Hot Chloride, Hot Caustic, Wet Hydrofluoric
Nickel Alloys	Hot Caustic, Hot Wet Hydrofluoric Acid
Titanium Alloys	Acidic Chloride, Nitric, Methanol, Hydrogenating Environments

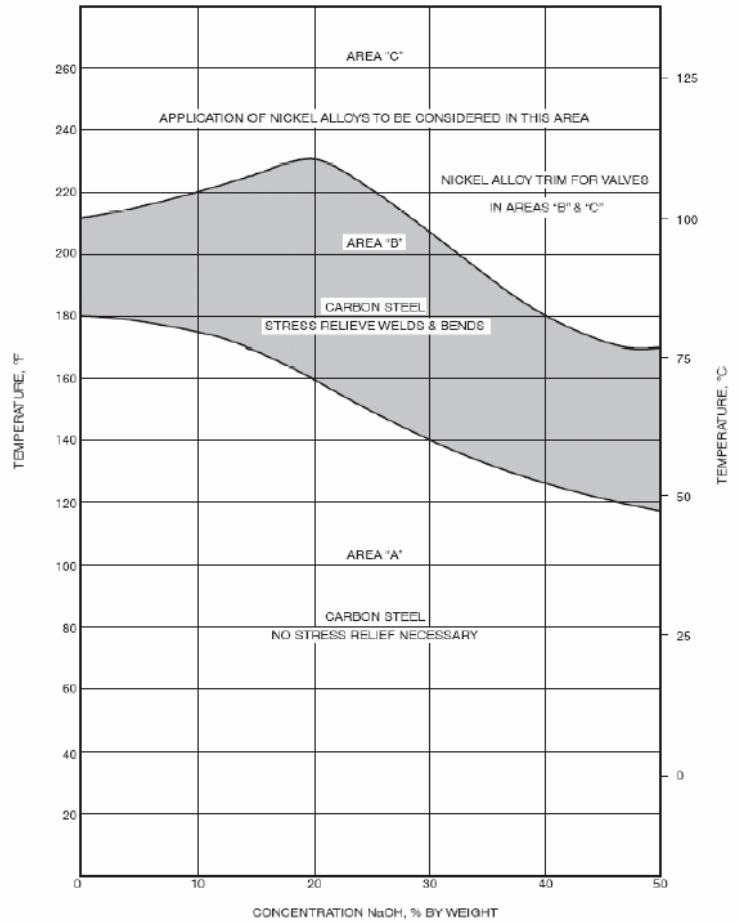

FIGURE 1 – Alloy selection for caustic service as a function of temperature and the caustic soda concentration

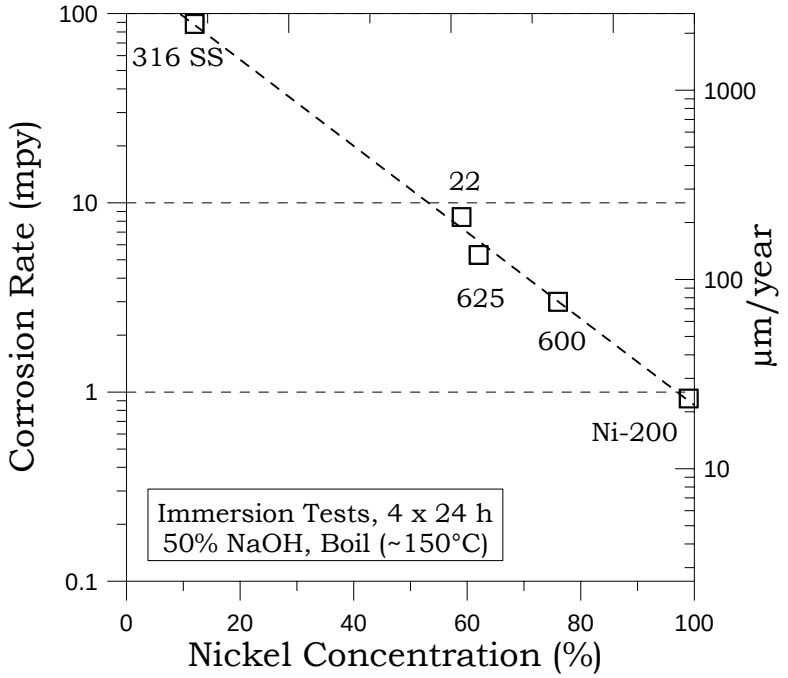

FIGURE 2 – General Corrosion Rate of Nickel Alloys and 316 SS in Boiling 50% NaOH
The higher the Ni content in the alloys the lower the corrosion rate